BETAVOLTAIC POWER SUPPLIES

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ABSTRACT

AstroPower is developing a gallium phosphide (GaP) based energy converter optimized for radio luminescent light-based power supplies. A "two-step" or "indirect" process is used where a phosphor is excited by radioactive decay products to produce light that is then converted to electricity by a photovoltaic energy converter. This indirect conversion of __radiation to electrical energy can be realized by applying recent developments in tritium based radio luminescent (RL) light sources in combination with the high conversion efficiencies that can be achieved under low illumination with low leakage, gallium phosphide based devices.

The approach of this research is to utilize the tritium fueled two step method to develop cost effective betavoltaic_batteries (_-batteries). The betavoltaic effect was discovered by Rappaport in 1953 (ref. 1). Soon after, the Elgin-Kidde (ref. 2) two-step, 5 year atomic battery was developed. This was based on $^{147}Pm/ZnS/Si$. Conversion efficiencies were low, and the subsequent development of Li based batteries quickly made the Elgin-Kidde cell obsolete. Olsen (ref. 3, ref. 4) has reported on the conversion efficiency of direct betavoltaic power supplies. A review of this technology reveals that there are three major limitations to the direct conversion approach.

<u>Direct Conversion</u>

- the activity and range of the beta emitter must be coupled to the diffusion length of the semiconductor material
- the power flux produced by a beta emitter cannot be concentrated
- the effective ionization energy of the converter material limits the efficiency of the device

<u>Indirect Conversion</u>

- the activity and range of the beta source is coupled to a phosphor which is chosen so that the light emitted is optimal for conversion by the semiconductor material.
- the use of down converting phosphors allows for a volumetric concentration of the beta energy in the form of light flux.
- energy loss is transferred to the phosphor which has experimentally demonstrated radioluminescent conversion efficiencies from 10 to 30%, depending on phosphor type and material quality.

Betavoltaic power generation requires an efficient semiconductor device to convert the beta-generated carriers into useful electric power. AstroPower has developed a gallium phosphide energy converter which is evaluated for two methods of power generation: direct conversion and indirect conversion. Figure 1 shows data for an indirect conversion array. For a ^{63}Ni-fueled direct conversion system, the short-circuit current density is $1.9x10^{-8}$ A/cm^2. The short-circuit current density for the indirect conversion system is $2.4x10^{-7}$ A/cm^2, better than an order of magnitude improvement over the ^{63}Ni fueled device. Improvements in current generation are the key to building betavoltaic power supplies with reasonable cost. Additionally, the utilization of tritium contributes to the safety of the device.

Results will be presented for GaP devices powered by Ni-63 and tritiarated phosphors. Betavoltaic converter leakage currents as low as $1.2x10^{-17}$ A/cm^2 have been measured and the temperature dependence of the reverse saturation current is found to have ideal behavior. The experimentally determined power density for a direct conversion ^{63}Ni fueled system is $1.35x10^{-8}$ W/cm^2 while the indirect conversion system power density was measured to be $1.9x10^{-7}$ W/cm^2. The significantly higher power available by the indirect conversion of beta radiation to electricity coupled with the safety of the tritium light source as opposed to ^{63}Ni is desirable for this application. Also of interest is that by using an indirect conversion method, even with a low level beta emitter such as tritium, more power can be generated than with a high beta flux using direct conversion methods.

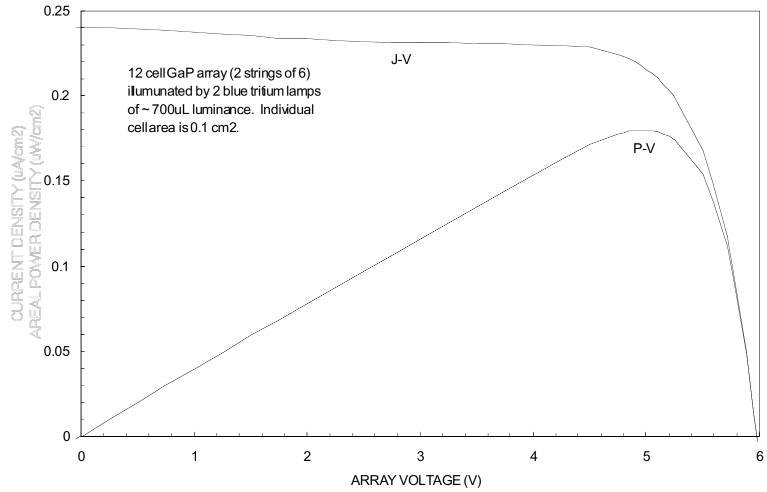

FIGURE 1. GaP betavoltaic array fueled by two custom-made T_2-ZnS:Ag light sources.

At the present time, work is ongoing in using tritium light sources to develop safe, high output light sources for a variety of applications. AstroPower is collaborating with Encapsulite, Inc. (Maplewood, NJ) to develop prototype betavoltaic generators using GaP-based devices and microsphere illumination technology. The microsphere concept, which is the high pressure encapsulation of tritium and phosphors in small (<1mm dia.) spheres, holds promise for the achievement of significantly brighter light sources. Encapsulite Inc. believes that luminance's of 1 to 10 FtL are possible using this approach. These light sources will enhance the power generating ability of the betavoltaic power conversion system by greatly increasing the incident light flux. The output of the betavoltaic generator is expected to be very stable since there are no semiconductor degradation mechanisms while the output of the generator assembly is expected to be predictable due to the well known decay statistics of the beta emitter. Useful generator lifetimes of 20-years are expected using tritium as a fuel.

Betavoltaic power generation using GaP devices and tritium powered light sources is technically feasible. A "realistic" power supply is proposed as having a V_{mp} of 5 V and an I_{sc} of 20 μA, which would require a converter area of approximately 140 cm^2 using a projected current generation density of 720 nA/cm^2. A much smaller device area is possible if the microsphere concept is as bright as expected. This configuration would find use in long-term space missions as a housekeeping power supply. This device could both store power for periodic burst transmissions and command/control receptions. It is also possible that this type of device could switch on a more powerful power source as the spacecraft reaches a vicinity where data acquisition activities are planned.

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4. Olsen, "Review of Betavoltaic Energy Conversion", Proceedings of the XII Space Photovoltaic Research and Technology Conference (SPRAT XII), NASA Lewis, Oct. 1992.
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Betavoltaic Power Supplies

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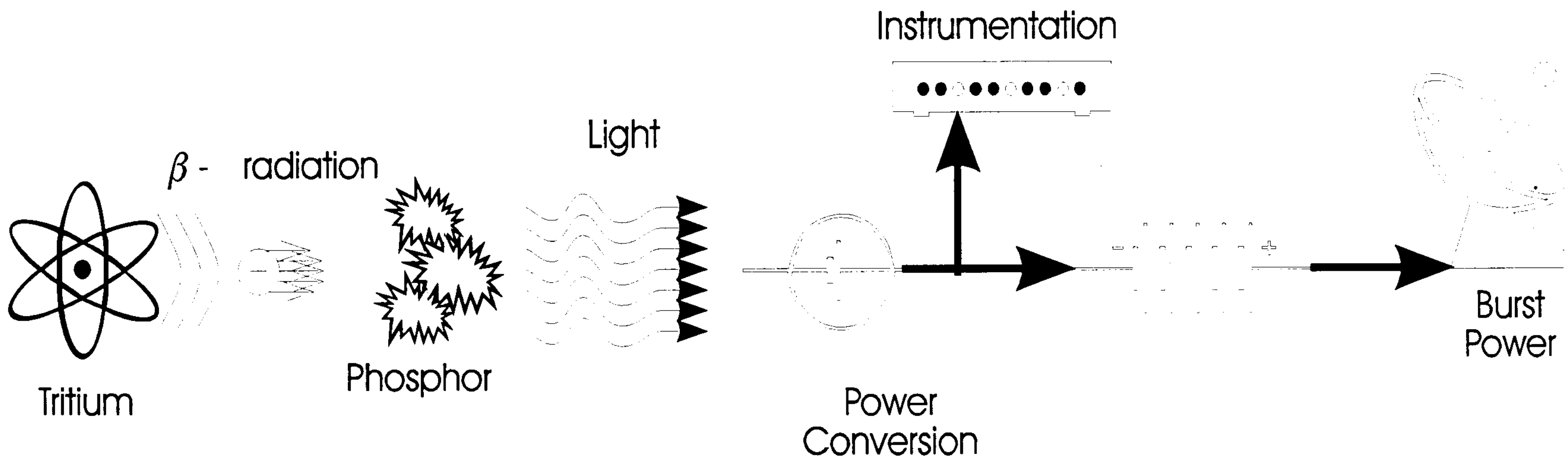
History and Theory

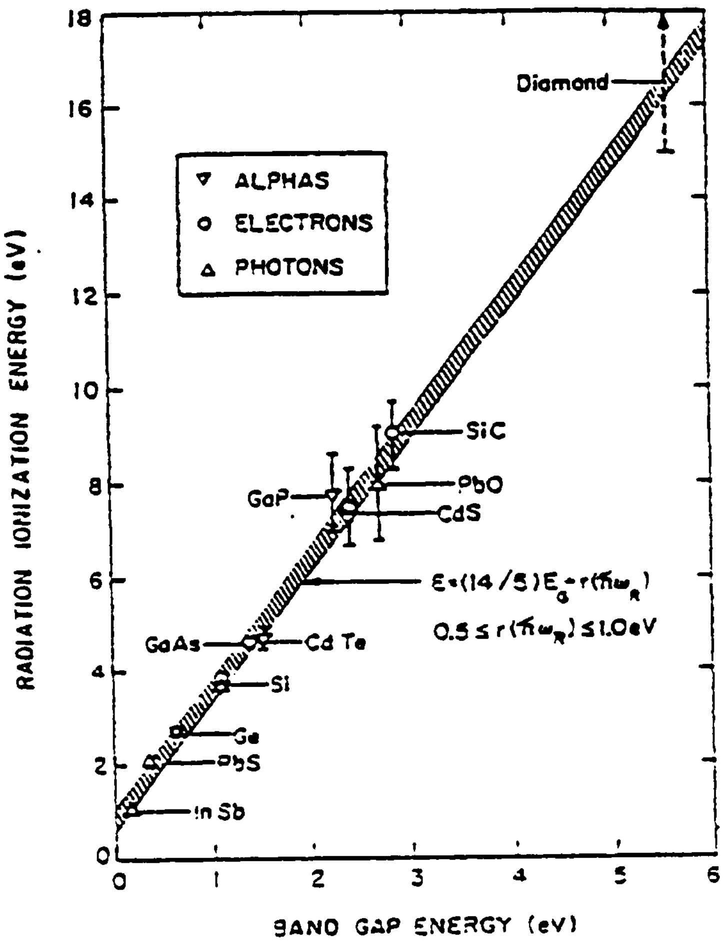


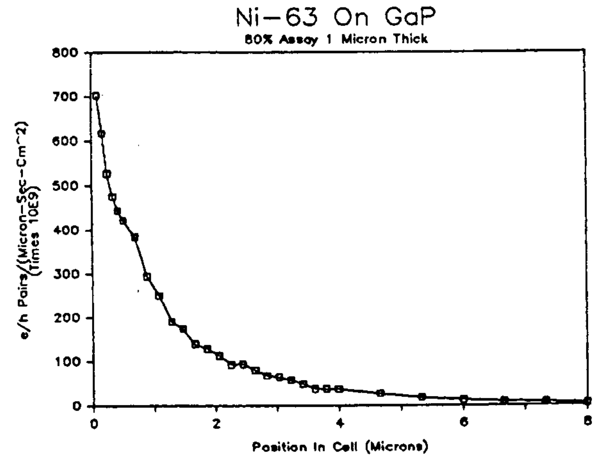
Direct vs. Indirect Betavoltaic Conversion

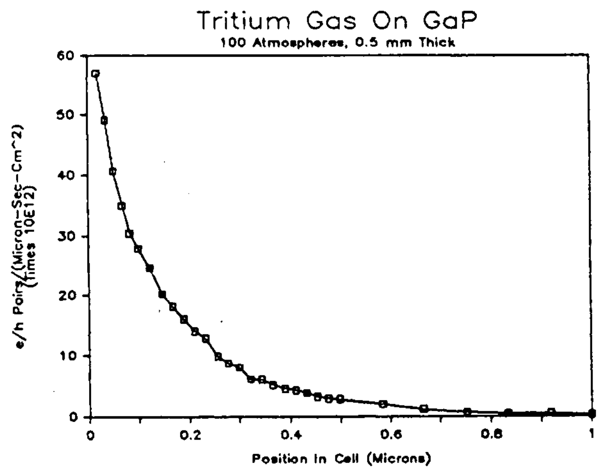
Possible Betavoltaic Fuels

Isotope	E_{max} (keV)	$\tau_{1/2}$ (yr)
H^3	18	12.3
Ni^{63}	67	92
Pm^{147}	230	2.62
Tl^{204}	765	3.75
Kr^{85}	670	10.9

Direct Betavoltaics -- Klein Equation and Absorption







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Direct Vs. Indirect Conversion

Direct Conversion

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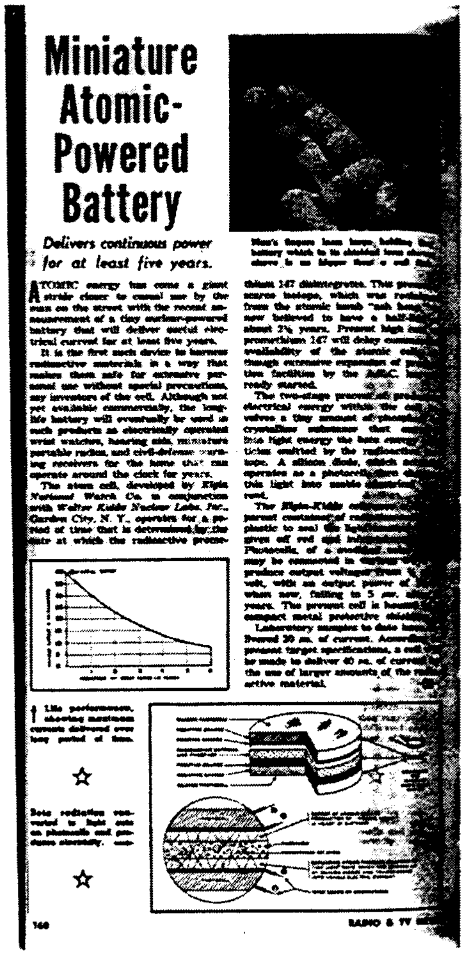
- energy loss is transferred to the phosphor which has experimentally demonstrated radioluminescent conversion efficiencies from 10 to 30%, depending on phosphor type and material quality.

Elgin-Kidde Cell -- Circa 1957



Miniature Atomic-Powered Battery

Delivers continuous power for at least five years.

- First attempt at commercial betavoltaics
- Two-step process --
  Pm147 --> ZnS --> light --> electricity (Si)
- Commercialization failed due to the development of efficient battery technology

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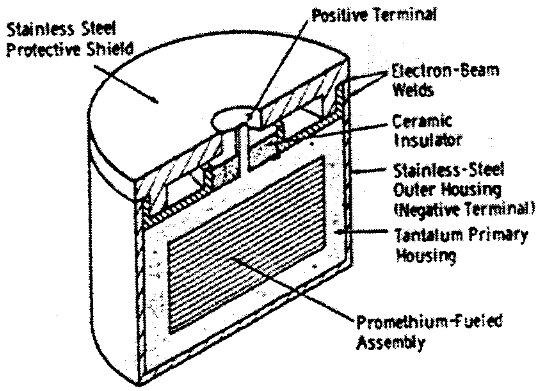
Betacel Circa 1972



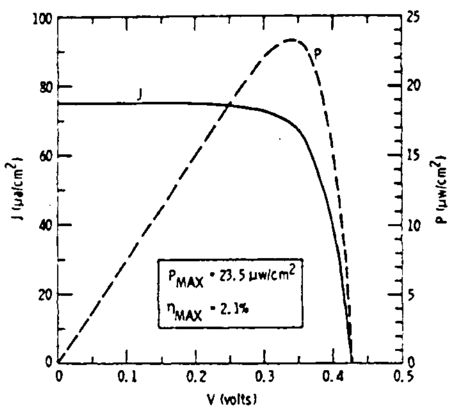


Fig. 2. Typical current-voltage curve for a Model 400 silicon cell coupled to a unidirectional Pm^{147} beta source consisting of 4·05 mg/cm² of Pm_2O_3 with an activity of 770 C/g.

- Second attempt at commercial betavoltaics
- Single step process
  Pm147 --> electricity (Si)
- Commercialization failed -- reasons never stated, but Si degradation and containment issues are suspected

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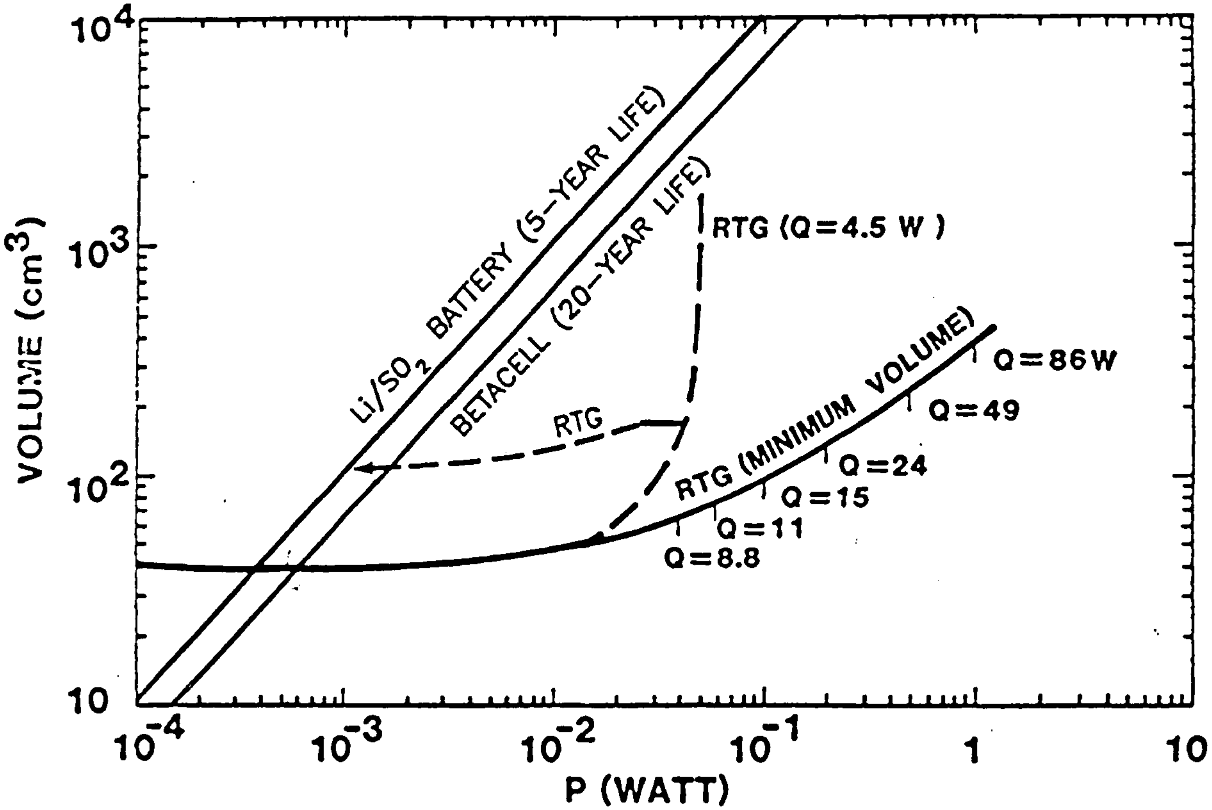
Sandia's Predictions



VOLUME COMPARISON FOR CONTINUOUS LOADS
(Modified from SAND 81-1759)

Tritium Properties

	Tritium Properties
Radiation emitted	β^-
Decay product	^3He
Max beta energy	18.6 keV
Avg. beta energy	5.68 keV
Half life	12.35 years
Specific activity	9.62×10^3 Ci/g
Power density	3.24×10^{-1} W/g
Activity density	2.37 Ci/cm^3 T_2 gas @ STP

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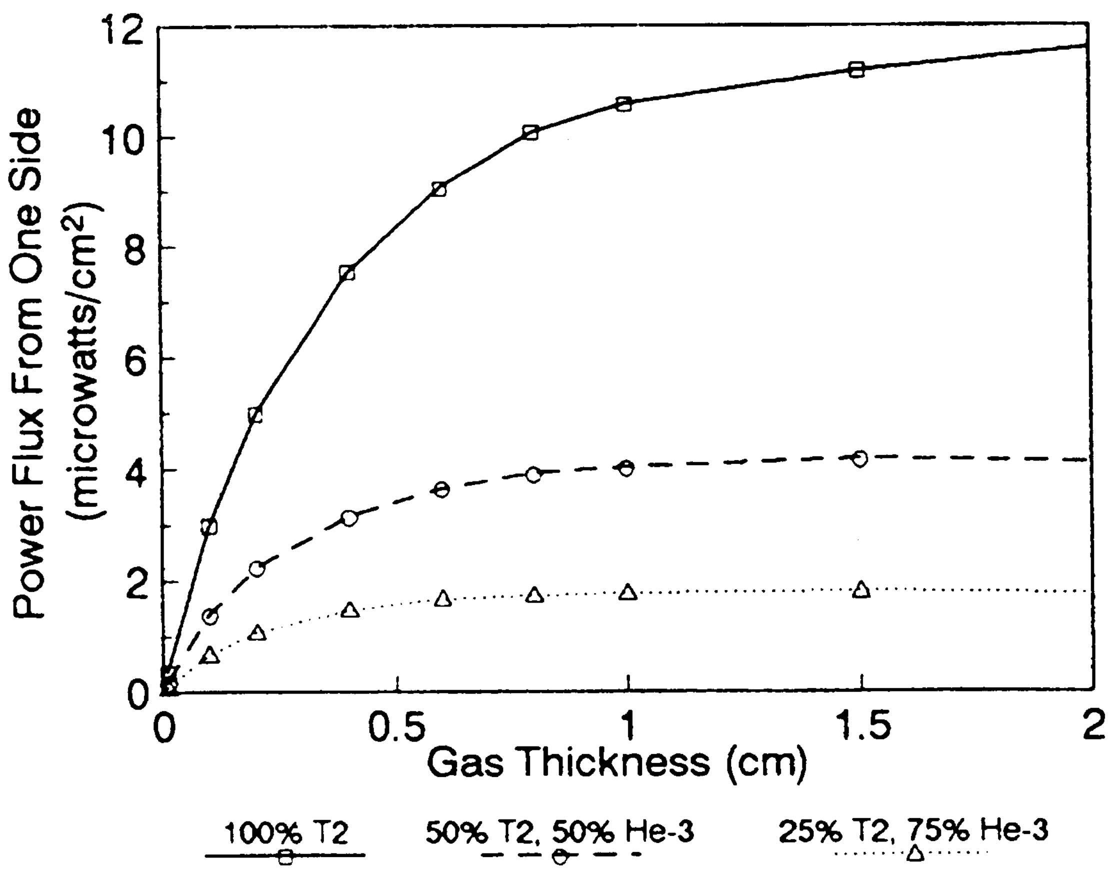
Tritium Power Flux



Walko, et. al., 1991

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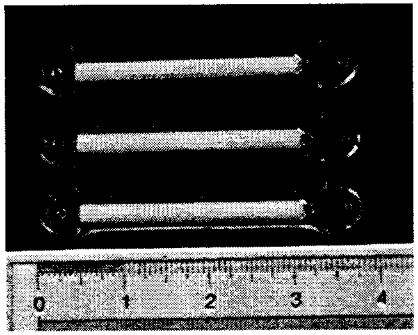
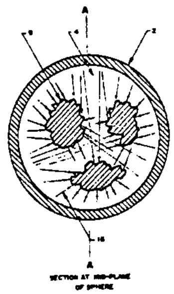
Tritium Light Sources



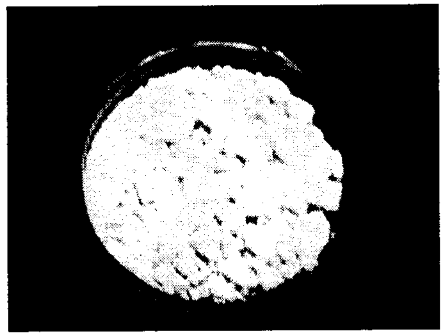
Standard Tritium Markers

- Commercially Available
  - Gunsights
  - Exit Signs
  - Watch Faces
- Not Very Bright



MicroSpheres

- Pre-Prototype
- Excellent Containment
- Expected to be Bright



Aerogels

- Pre-Prototype
- Expected to be very Bright

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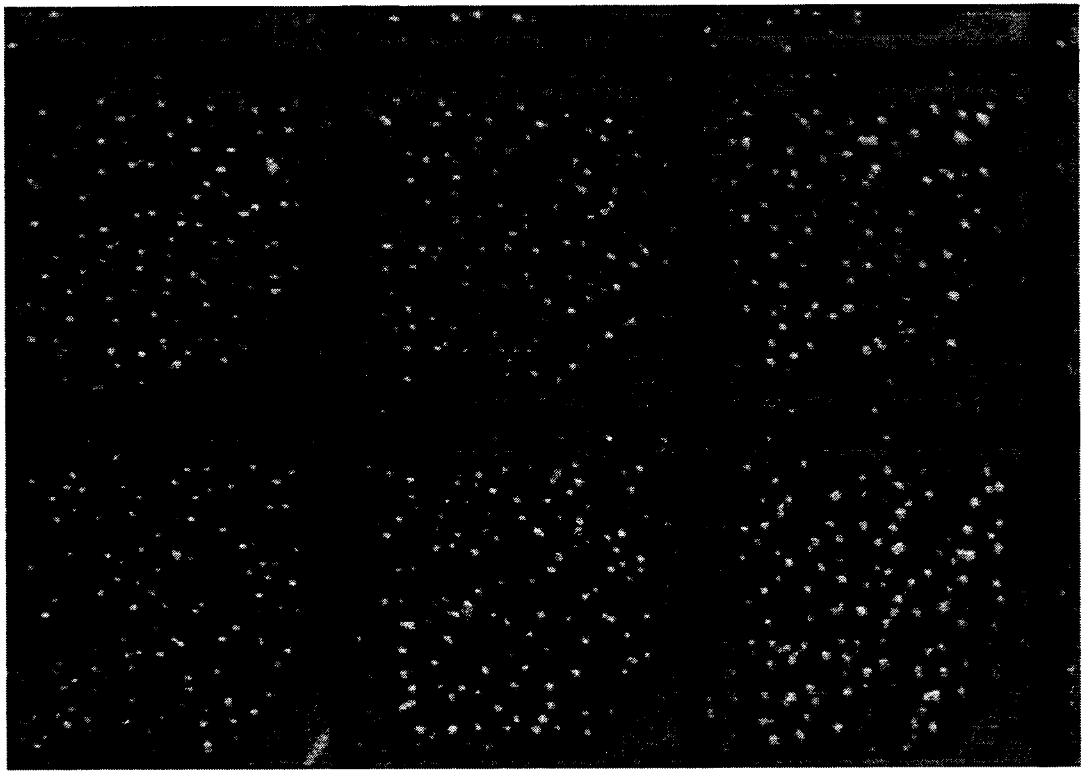
Experimental Results



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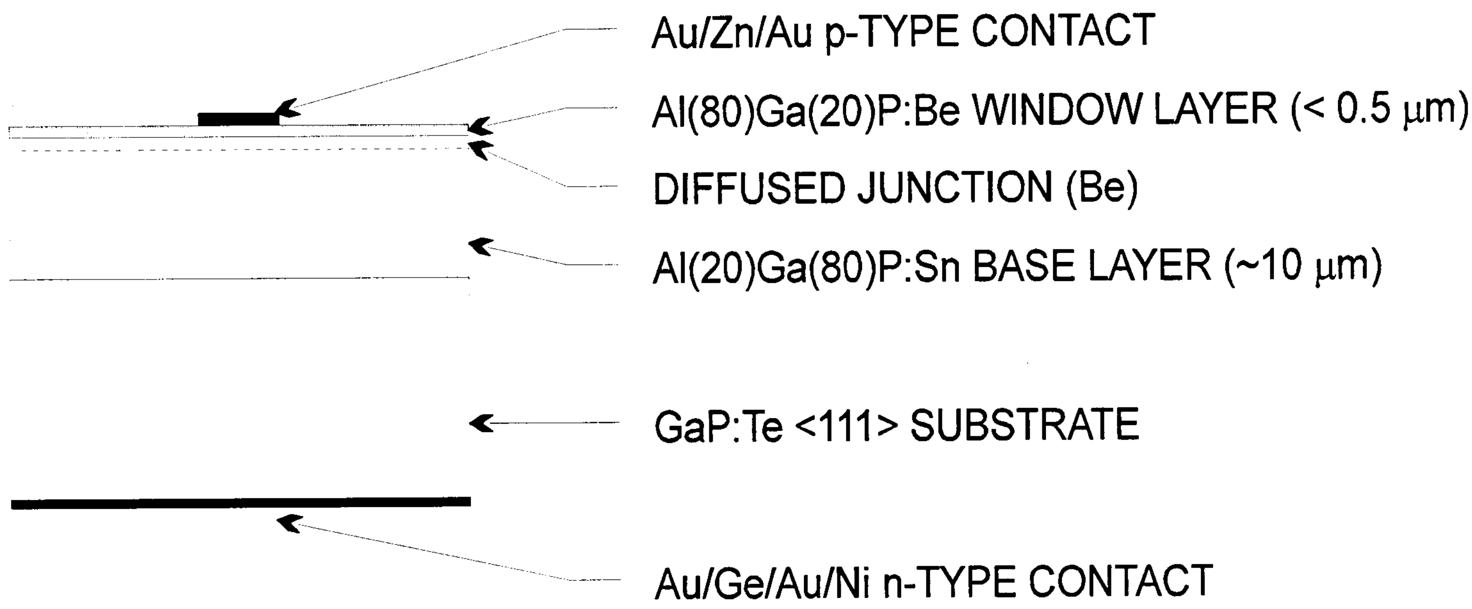
GaP Photodiode Structure



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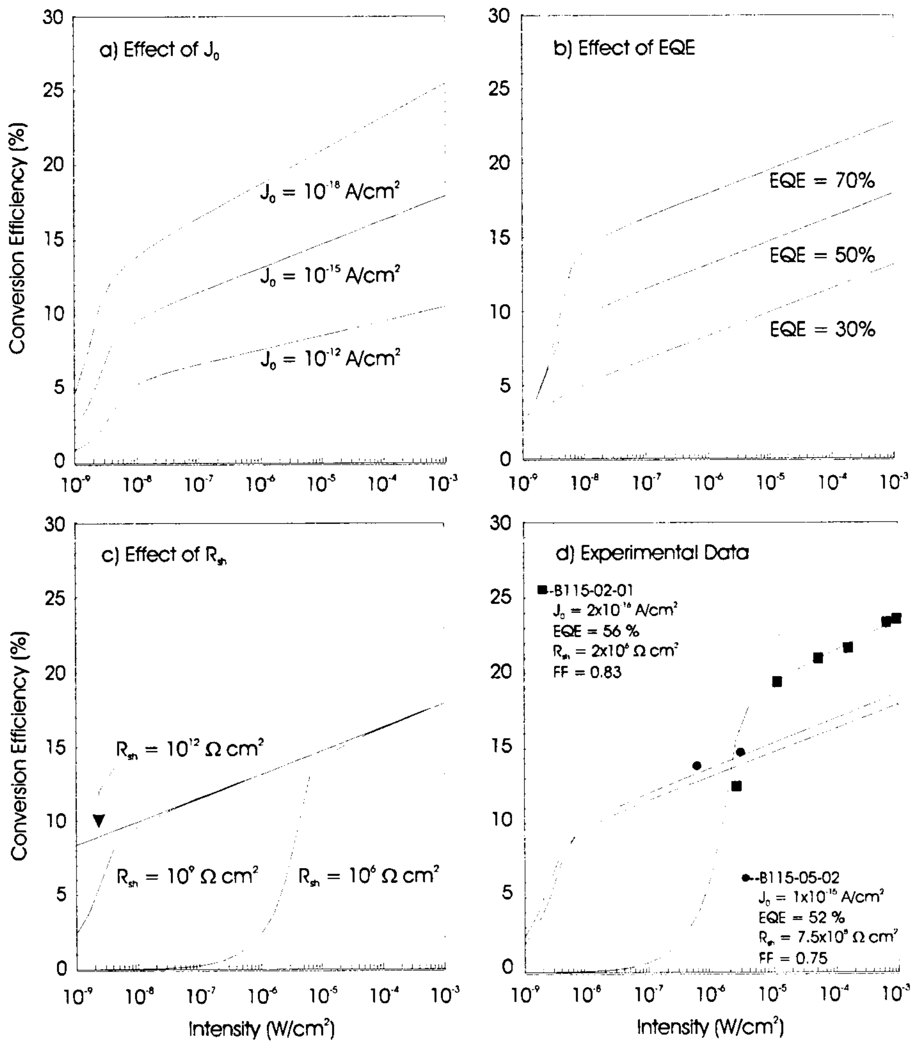
Modeled Device Efficiency



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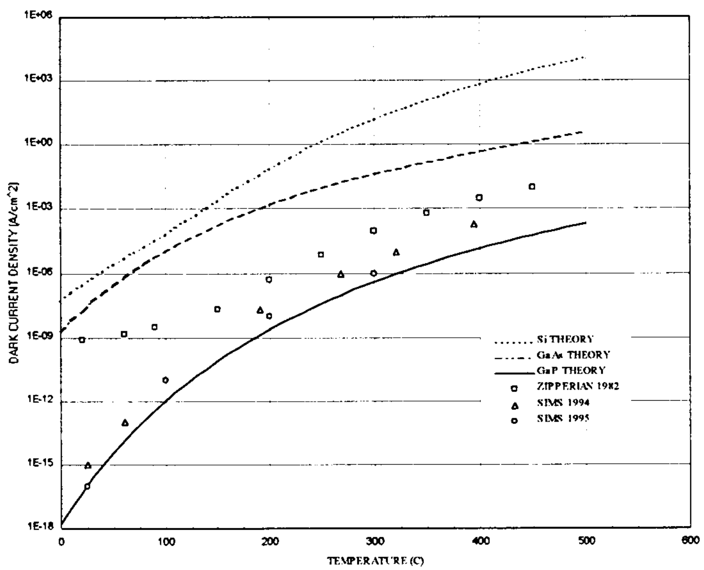
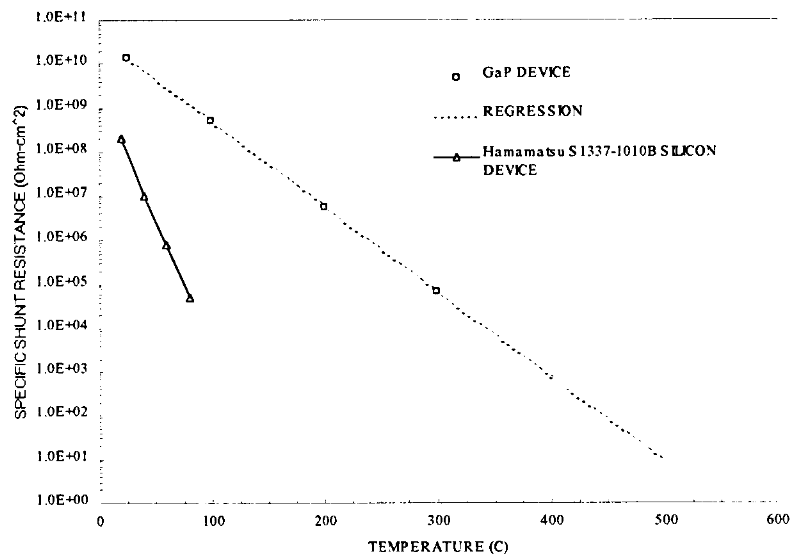
GaP Leakage Currents and Shunt Resistance





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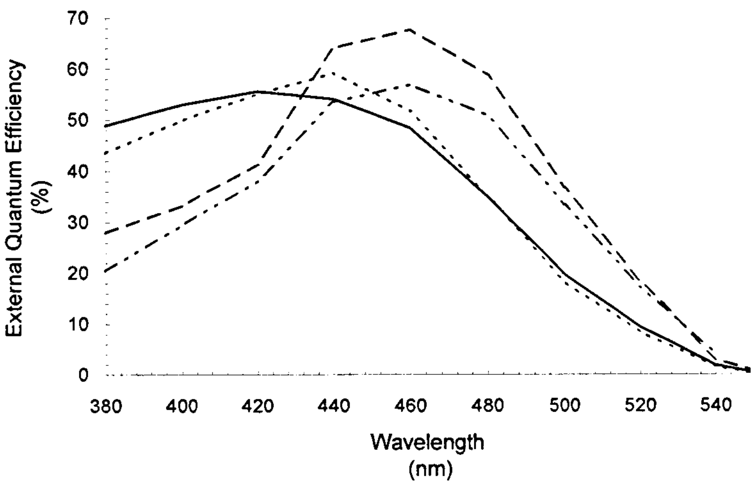
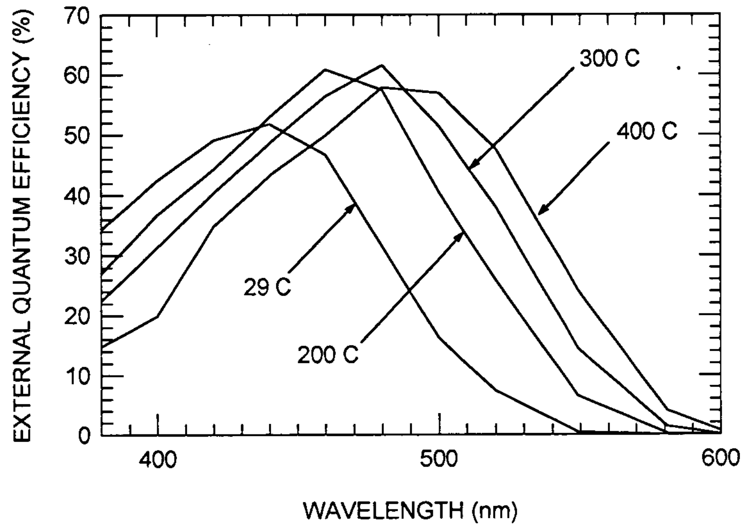
GaP Quantum Efficiency





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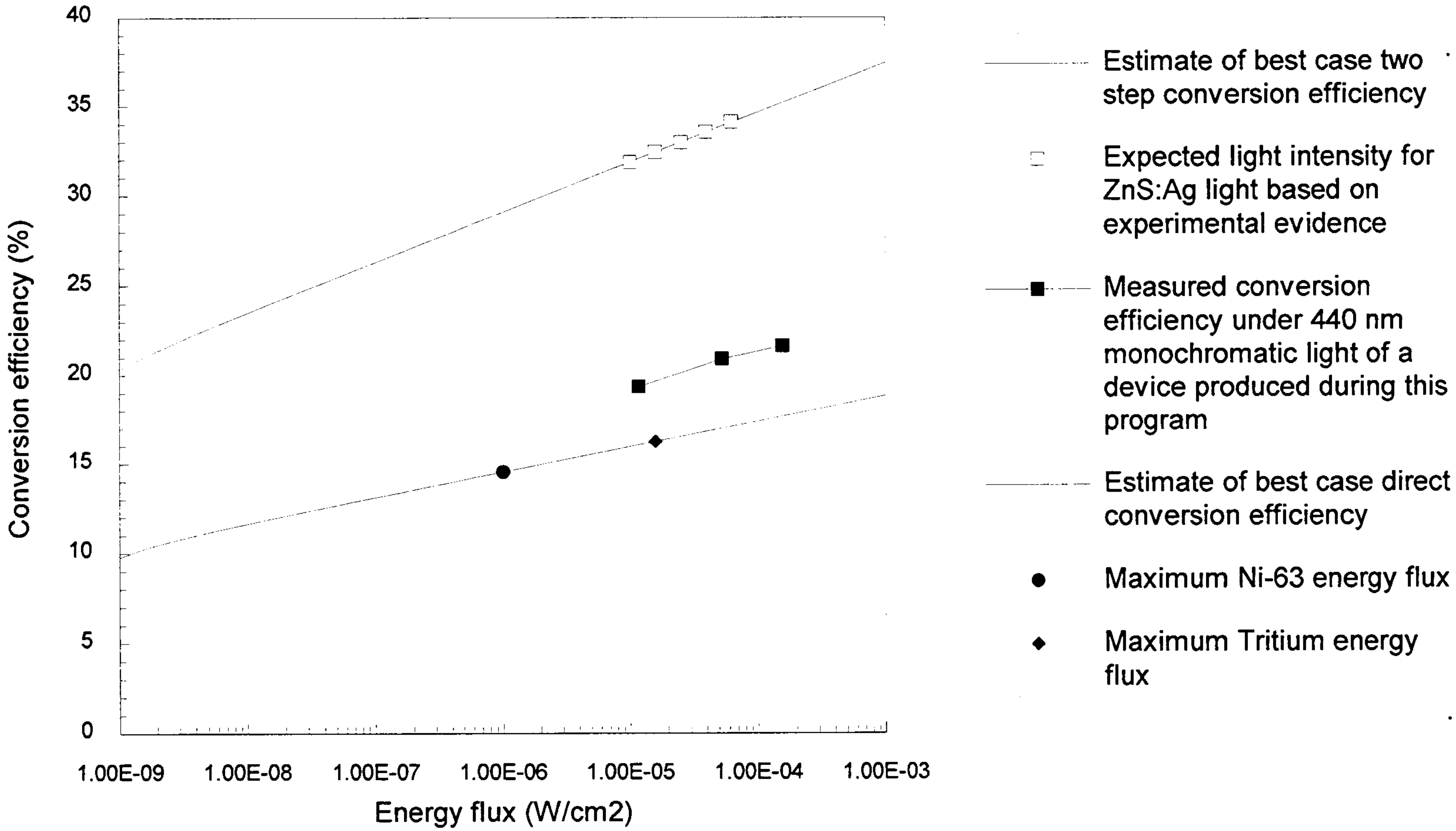
Modeled Conversion Efficiency



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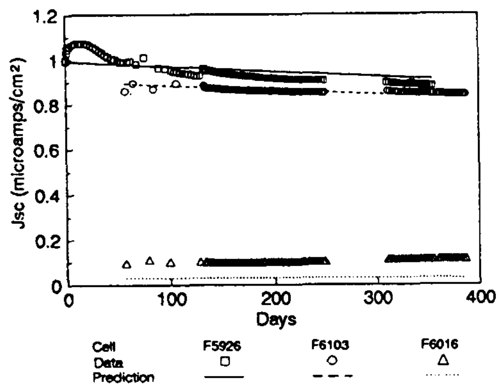
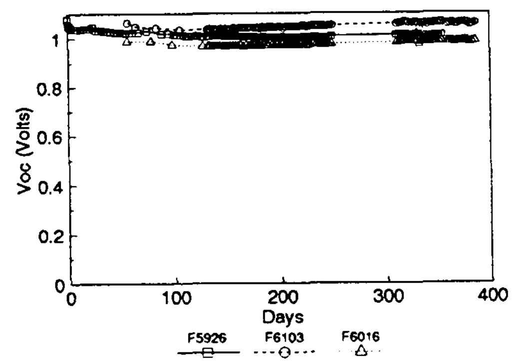
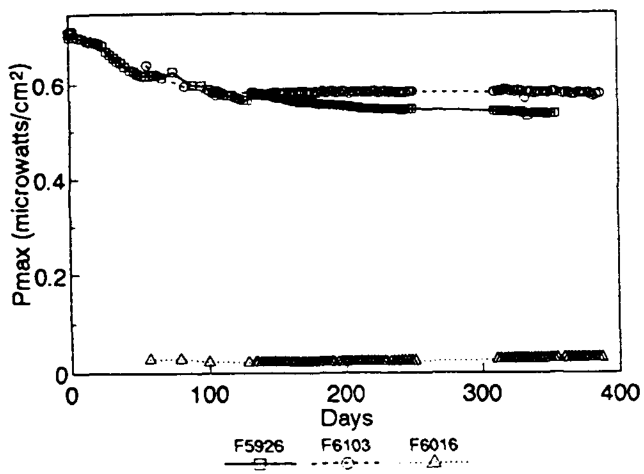
Tritium-Fueled GaP Betacell







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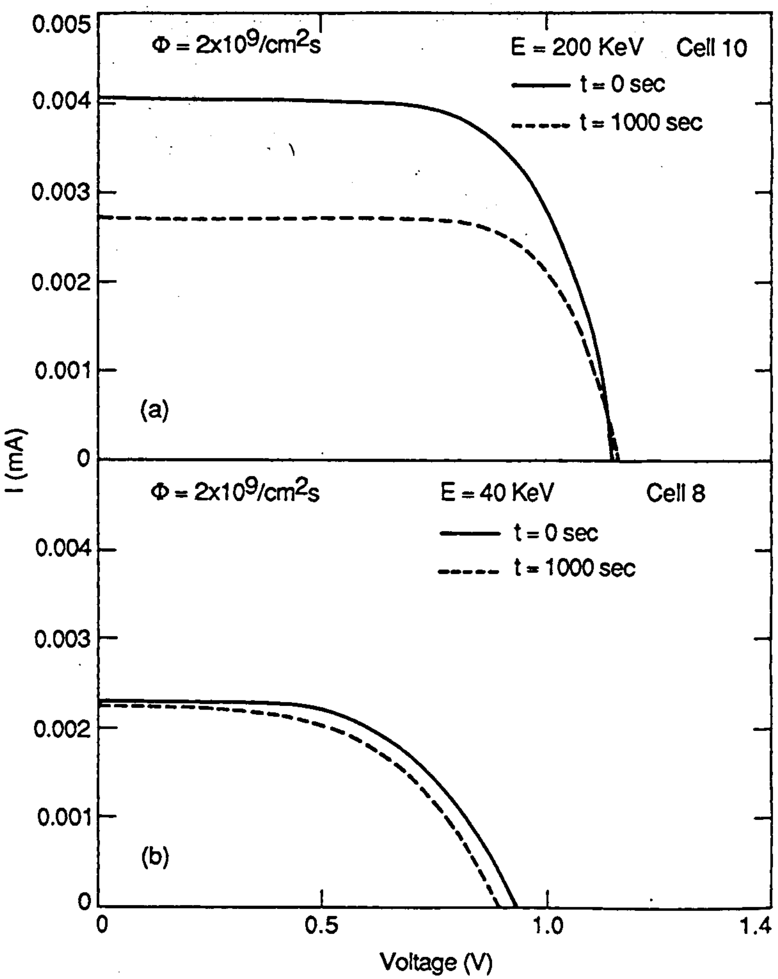
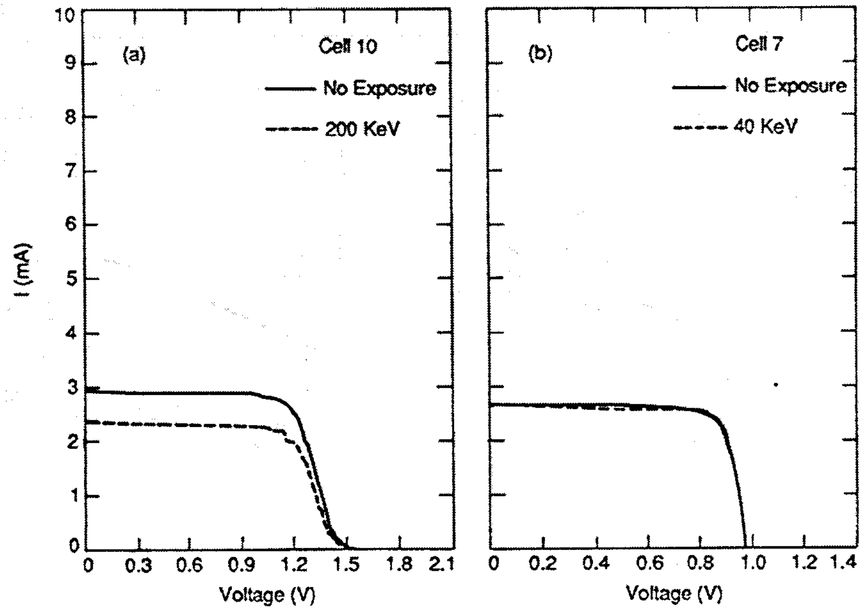
GaP Radiation Hardness

BETAVOLTAIC I-V GaP





Pool, et. al, 1989

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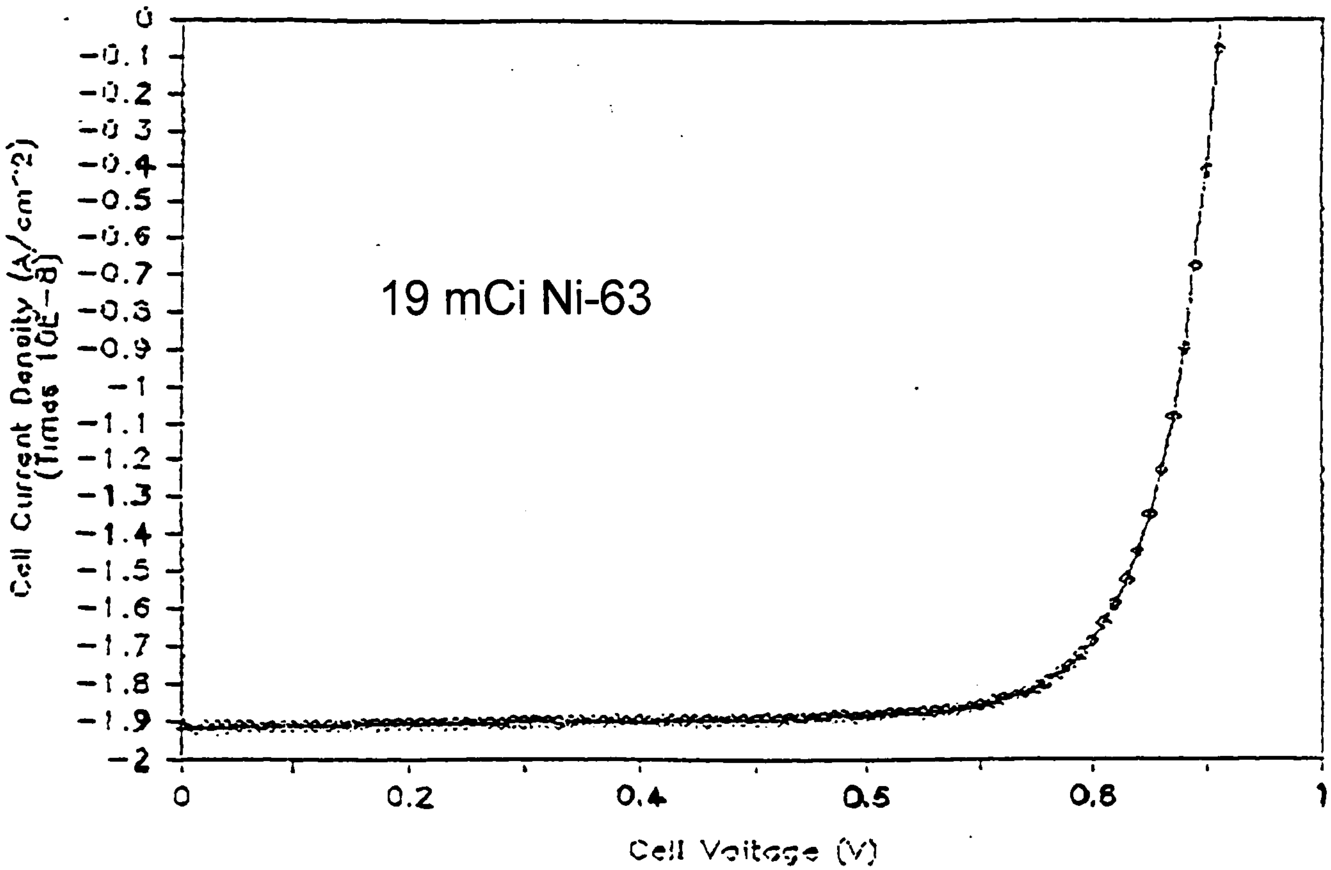
Ni-63 Fueled GaP Betacell



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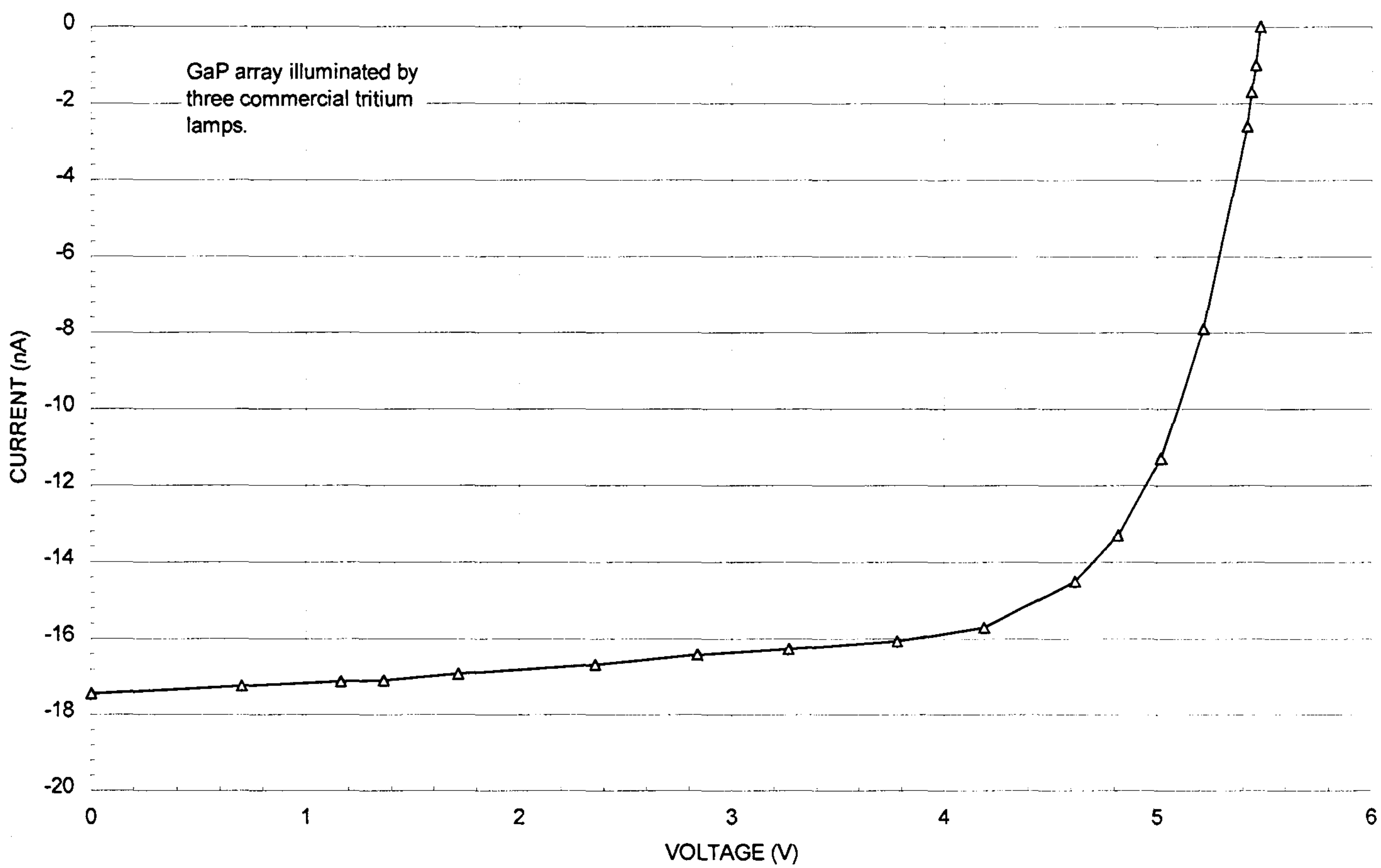
Tritium -> ZnS:Ag -> GaP -> Electricity



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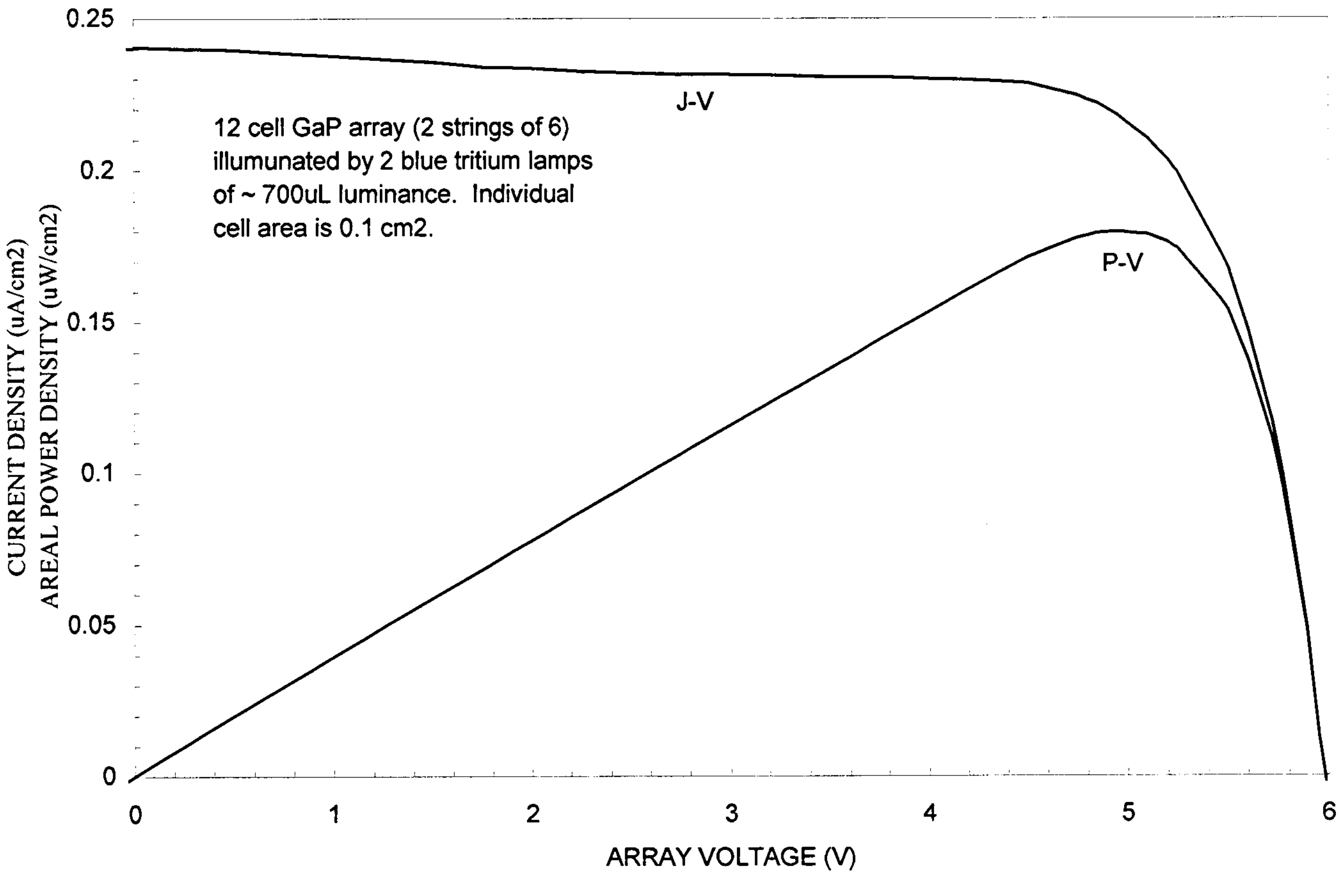

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GaP Power Conversion at Different Light Levels

Case	Light Source	V_{oc} (V) (1 cell)	J_{sc} ($\mu A/cm^2$)	Power Density ($\mu W/cm^2$)
1	Dim white light from a computer monitor bounced off a ceiling to impinge on the array	0.7	0.006	0.003
2	Moonlight (Full, ~ AM1.5-0.001X)	0.9	0.020	0.014
3	Tritium Light (ZnS:Ag -- Blue ~ 700 μL)	1.0	0.240	0.179
4	Indirect sunlight through a 1.45 cm^2 aperture	1.1	1.395	1.163
5	Roomlight (Fluorescent lights)	1.2	4.750	4.251
6	Indirect sunlight through a 7.23 cm^2 aperture	1.2	8.000	7.380
7	Indirect sunlight through a 14.5 cm^2 aperture	1.3	12.800	12.130
8	Direct sunlight (AM0-1X)	1.5	715.000	795.400

Deployment Issues

- Customers -- Betavoltaics is very expensive and has a low power density. To date, no one has needed betavoltaics enough to pay for deployment.
- Energy Converters -- The GaP-based energy converters discussed are close to the theoretical limits. They are also the most cost-effective of the high-bandgap materials available.
- Light Sources -- There is room for ~ 10x improvement in brightness of advanced tritium lights compared to commercial tritium lights. The aerogel and microsphere approaches look promising.
- A strawman 100 microwatt betavoltaic generator will require ~140 cm^2 of GaP converter cells using currently available light sources.